A CONSERVATIVE ESTIMATE OF THE
METEOROID PENETRATING FLUX

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P-1913

February 11, 1960

To be published in the proceedings of SNAP sponsored symposium on meteoroid penetration.

I. INTRODUCTION

In early December, 1959, the Aircraft Reactors Branch of the Atomic Energy Commission held a symposium for the purpose of assessing the meteoroid hazard to space power stations being designed under the SNAP program. The stations generally contain a nuclear reactor which powers an electrical generator. Operating the reactor in space requires the use of a large area radiator whose weight is influenced drastically by the criterion that it must survive the meteoroid hazard. For the larger reactors the skin thickness required for structural strength is very small compared with that required to shield the radiator's interior against meteoroid penetration. Since the radiator weight comprises an important portion of the total system weight, it is essential to minimize it, which requires an accurate knowledge of the meteoroid hazard itself.

From among the participants of the symposium, the ARB appointed an ad hoc committee* to formulate the best estimate of the hazard. In a subsequent meeting this committee decided that in formulating the estimate, only knowledge currently available should be used, and that one should not attempt to guess the results of pending or future research. This excludes from consideration such things as meteor bumpers, for which it is felt that current knowledge is preliminary and sketchy. Another condition imposed was that the estimate be conservative in cases where uncertainties were felt to exist. This meeting set the philosophy used in writing this paper.

As a result, it is felt that structures designed according to the laws set forth herein will be very reliable, and that future measurements

*The members were R. L. Bjork, of The RAND Corporation, M. G. Coombs, of Atomics International, and D. H. Silvern, Engineering Consultant.

and research will enable the weights of the structures to be decreased, rather than to force an increase in them.

The problem is naturally divided into two parts:

1) Estimating the flux of meteoroids as a function of velocity, mass, and density.

2) Estimating the effect of a meteoroid of given velocity, mass, and density.

In the following, these two estimates are made, and from them the penetrating flux is deduced for a sheet of aluminum or steel in space.

II. ESTIMATES OF METEOROID FLUX

MASS VERSUS FREQUENCY

The largest uncertainties occur in the first part, particularly in the estimates regarding mass. The agreement among the various workers in this field regarding the flux as a function of meteor magnitude is quite good. The large uncertainty arises in translating magnitude into mass, where the spread of estimates encompasses about a factor of a thousand. The estimate chosen as best is due to Whipple.[1] The two main reasons for the selection are that it is the most conservative, predicting the largest flux for a given mass, and its extrapolation to the micrometeoroid region agrees well with the satellite data taken there. Figure 1 presents Whipple's estimates together with the significant satellite data points.

At the symposium Whipple stated that the mass of a zero-magnitude meteor will lie in the range of 1 to 30 gm. This range of uncertainty is reflected by the shaded region of Fig. 1, so that using the upper line of that region is a conservative estimate. The line lies somewhat below the

satellite points.

Among the rocket and satellite observations taken on micrometeoroids, there are two sets of data which overshadow the rest in statistical significance. These are the α 1958 (Explorer I) data, which recorded 153 clear impacts over a 12 day observation period,[2,3] and the η 1959 (Vanguard III) data for which about 1500 impacts have been analyzed to date, taken over a period of some 50 days. Both sets recorded fluctuations of about a factor of ten in the number of impacts recorded from day to day. This fact indicates that data taken over only short time periods should be regarded as relatively insignificant, and so eliminates the other satellite and rocket data from consideration.

The Sputnik III data probably qualifies from the standpoint of area-time exposure, but was disregarded because the results have been altered by a factor of about 10,000 by various Russian data interpretation schemes.[4] Also, the number of impacts recorded has not been given.

Both the satellite data, the radio meteor data, and the photographic meteor data can be fit by slightly increasing the slope of Whipple's extrapolation. Again, the change is in the conservative direction. The final estimate chosen was

$$\phi = 10^{-12}\, m^{-10/9} \tag{1}$$

where ϕ is the flux in impacts per square meter per second of particles greater than mass, m, and m is in grams. The line defined by Eq. (1) is also shown in Fig. 1

Meteoroid Density

Another uncertainty arises in the estimate of meteoroid density. The only direct estimate of density has been given by Whipple.[1] In the single

case treated to date, involving a meteor of first magnitude, he computed the density to be .05 gm/cm^3. Impacts by such a large meteoroid on a space vehicle will be an extremely rare occurrence, and the most important damage is to be expected from meteoroids whose mass is less than one-thousandth of that of a first magnitude one. It is deemed unlikely that the smaller ones would have such a porous structure as the one measured. Whipple believes that as the size of meteoroids decreases, their density is likely to increase, finally approaching the density of stone at the very small size limit. Since there is no sure way to estimate the density as a function of mass, the conservative approach dictates that one assign the density of stone to all meteoroids.

All impact data taken in laboratories to date indicates that among particles of the same mass and velocity, the one of greatest density gives the largest penetration.[5] It has been found that the penetration may be empirically correlated with the density ratio of projectile and target through the use of a factor of the type $(\rho_p/\rho_t)^\alpha$. The values of α range between .3 and .6, depending on the target material. However, the velocities used in establishing this relation range from about 2 to 4 km/sec, and the projectile densities are greater than 1.5 gm/cm^3. It would be too optimistic to expect that the same relation holds for velocities 7 times higher and densities 30 times lower than those used in making the empirical fit. But it does seem plausible to expect that the general trend will be the same, so that overestimating the density results in overestimating the penetration.

Accordingly, it will be assumed here that meteoroids have the density of stone, about 2.8 gm/cm^3. If future research shows that the important meteoroids have densities of .05 gm/cm^3, and if the correction factor is

found to be valid using a conservative α of 0.3, the estimated penetration will be reduced by a factor of 3.3 and 4.6 for aluminum and steel, respectively. However, one should not count on this bonus until the appropriate measurements or calculations have been made.

III. PENETRATION ESTIMATES

For the second part of the problem, the work of the author was used.[(6)] The calculations are based on a numerical solution of a hydrodynamic model of the impact process which assumes that the material's strength is negligible compared with the forces at work during the process. They were made over the velocity range of 5.5 to 72 km/sec, but were restricted to impacts of aluminum projectiles on aluminum targets and iron projectiles on iron targets. In the range of pressures developed in the impact, iron and steel behave identically. The results may be summarized in the equations:

$$\begin{aligned} &\text{Al on Al:} \quad p = 1.09\ (mv)^{1/3} \\ &\text{Fe on Fe:} \quad p = .606\ (mv)^{1/3} \end{aligned} \tag{2}$$

where p is the penetration depth in cm, m is the projectile mass in gm, and v is the impact velocity in km/sec. The calculated penetration depths fit experimental points taken at 6.3 and 6.8 km/sec for aluminum and steel, respectively. Both the calculated and experimental craters are hemispherical with radius, p.

The calculations were made for thick targets, but enough information was obtained to deduce that if a projectile penetrates a depth, p, in a

thick target it will just penetrate a sheet of the same target material which is 1.5p thick.

IV. PENETRATING FLUX

Combining the expressions for the flux and penetration, one finds that the flux of particles which will penetrate a sheet of thickness, t, is given by

$$\psi = 10^{-12}\, t^{-10/3}\, K^{10/3}\, v^{10/9} \left(\frac{\rho_p}{\rho_t}\right)^{\frac{10}{3}\alpha} \tag{3}$$

where $K_{Al} = 1.5(1.09) = 1.64$ and $K_{Fe} = 1.5(.605) = .908$. ψ is given in penetrations/m^2/sec, t in cm, and v in km/sec.

The density ratio is close to unity for aluminum ($\rho_t = 2.7$) and less than unity for steel ($\rho_t = 7.9$) if the meteoroid density is taken to be 2.8. The limiting empirical values of α lead to powers of the density ratio between one and two in Eq. (3). As argued previously, the density ratio should be eliminated from Eq. (3) for the present, and it is included only to illustrate the manner in which it might be expected to enter when sufficient information becomes available.

The estimates of the penetrating flux are summarized in Table I and Fig. 2. The first three columns of Table I represent Whipple's best estimates of the mass and velocity of meteors as a function of their "visual magnitude." As the very small meteors cannot be detected by any optical means, the term, "visual magnitude" is applied to them only by analogy. As used by Whipple, it is really a measure of mass, according to the law

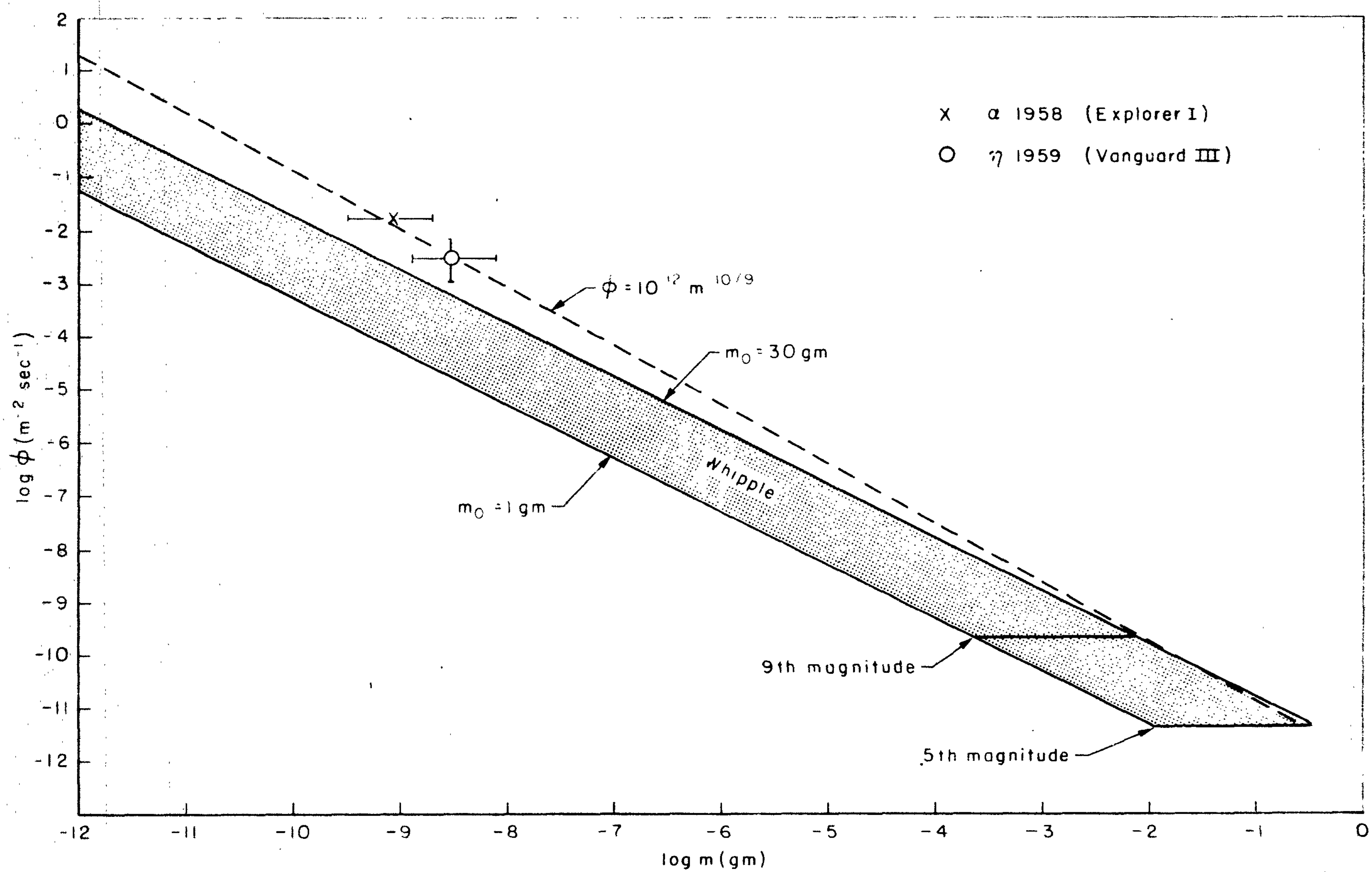
$$M = 2.5 \log_{10} (m_o/m)$$

where M is the magnitude, m the mass of the meteor, and m_o the mass of a zero-magnitude meteor. The uncertainty in m_o previously cited thus pervades the entire magnitude scale.

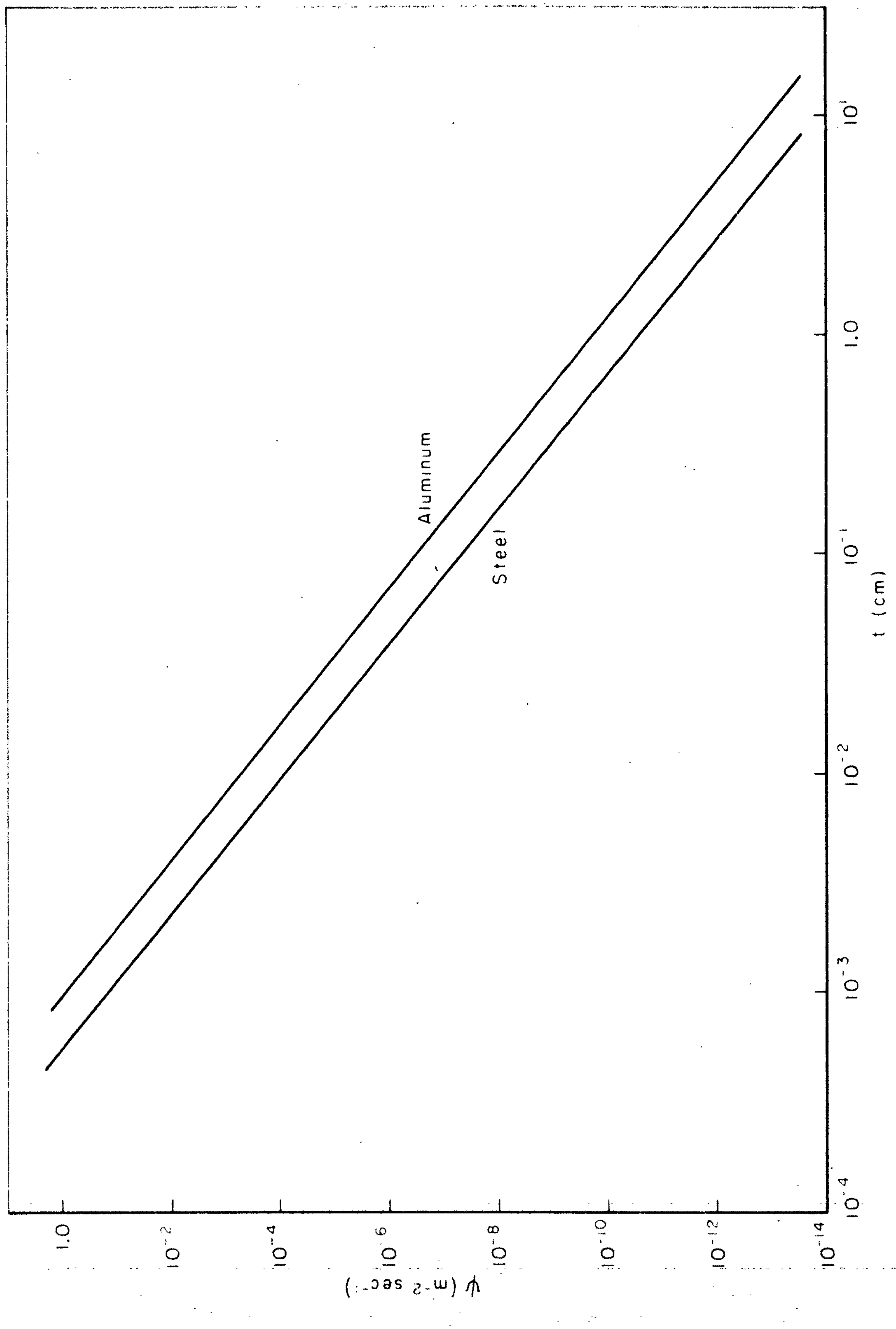
The fourth and fifth columns give the sheet thicknesses of aluminum and steel, respectively, which these meteoroids will just penetrate, calculated according to Eq. (2). The last column is the flux calculated by Eq. (1). The last three columns are presented in Fig. 2. The penetration flux for steel has been computed using Eq. (2), which is equivalent to assuming that the meteoroids are steel. This represents another overestimate which may be removed when more is learned of the composition and penetrating properties of meteoroids.

TABLE I

Visual Magnitude	Mass gm	Velocity km/sec	Aluminum Thickness cm	Steel Thickness cm	Penetrating Flux Penetration/m^2 sec
0	25.0	28.0	14.5	8.06	2.80×10^{-14}
1	9.95	28.0	10.7	5.93	7.79×10^{-14}
2	3.96	28.0	7.85	4.36	2.17×10^{-13}
3	1.58	28.0	5.78	3.21	6.02×10^{-13}
4	.628	28.0	4.25	2.36	1.68×10^{-12}
5	.250	28.0	3.13	1.74	4.67×10^{-12}
6	9.95×10^{-2}	28.0	2.30	1.28	1.30×10^{-11}
7	3.96×10^{-2}	28.0	1.69	.940	3.62×10^{-11}
8	1.58×10^{-2}	27.0	1.23	.684	1.00×10^{-10}
9	6.28×10^{-3}	26.0	.894	.496	2.80×10^{-10}
10	2.50×10^{-3}	25.0	.649	.360	7.78×10^{-10}
11	9.95×10^{-4}	24.0	.471	.261	2.17×10^{-9}
12	3.96×10^{-4}	23.0	.341	.190	6.03×10^{-9}
13	1.58×10^{-4}	22.0	.248	.138	1.67×10^{-8}
14	6.28×10^{-5}	21.0	.179	9.96×10^{-2}	4.67×10^{-8}
15	2.50×10^{-5}	20.0	.130	7.21×10^{-2}	1.30×10^{-7}
16	9.95×10^{-6}	19.0	9.38×10^{-2}	5.21×10^{-2}	3.61×10^{-7}
17	3.96×10^{-6}	18.0	6.78×10^{-2}	3.76×10^{-2}	1.01×10^{-6}
18	1.58×10^{-6}	17.0	4.90×10^{-2}	2.72×10^{-2}	2.79×10^{-6}
19	6.28×10^{-7}	16.0	3.53×10^{-2}	1.96×10^{-2}	7.78×10^{-6}
20	2.50×10^{-7}	15.0	2.54×10^{-2}	1.41×10^{-2}	2.17×10^{-5}
21	9.95×10^{-8}	15.0	1.87×10^{-2}	1.04×10^{-2}	6.03×10^{-5}
22	3.96×10^{-8}	15.0	1.37×10^{-2}	7.63×10^{-3}	1.68×10^{-4}
23	1.58×10^{-8}	15.0	1.01×10^{-2}	5.62×10^{-3}	4.66×10^{-4}
24	6.28×10^{-9}	15.0	7.44×10^{-3}	4.13×10^{-3}	1.30×10^{-3}
25	2.50×10^{-9}	15.0	5.47×10^{-3}	3.04×10^{-3}	3.61×10^{-3}
26	9.95×10^{-10}	15.0	4.03×10^{-3}	2.24×10^{-3}	1.01×10^{-2}
27	3.96×10^{-10}	15.0	2.96×10^{-3}	1.64×10^{-3}	2.80×10^{-2}
28	1.58×10^{-10}	15.0	2.18×10^{-3}	1.21×10^{-3}	7.77×10^{-2}
29	6.28×10^{-11}	15.0	1.60×10^{-3}	8.90×10^{-4}	.217
30	2.50×10^{-11}	15.0	1.18×10^{-3}	6.55×10^{-4}	.603
31	9.95×10^{-12}	15.0	8.67×10^{-4}	4.82×10^{-4}	1.68



Meteoroid flux versus mass near earth



Penetrating meteoroid flux near earth versus skin thickness

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